

Test and Evaluation Metrics of Crew Decision-Making And Aircraft Attitude and Energy State Awareness

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NASA has established a technical challenge, under the Aviation Safety Program, Vehicle Systems Safety Technologies project, to improve crew decision-making and response in complex situations. The specific objective of this challenge is to develop data and technologies which may increase a pilot's (crew's) ability to avoid, detect, and recover from adverse events that could otherwise result in accidents/incidents. Within this technical challenge, a cooperative industry-government research program has been established to develop innovative flight deck-based counter-measures that can improve the crew's ability to avoid, detect, mitigate, and recover from unsafe loss-of-aircraft state awareness – specifically, the loss of attitude awareness (i.e., Spatial Disorientation, SD) or the loss-of-energy state awareness (LESA). A critical component of this research is to develop specific and quantifiable metrics which identify decision-making and the decision-making influences during simulation and flight testing. This paper reviews existing metrics and methods for SD testing and criteria for establishing visual dominance. The development of Crew State Monitoring technologies – eye tracking and other psychophysiological – are also discussed as well as emerging new metrics for identifying channelized attention and excessive pilot workload, both of which have been shown to contribute to SD/LESA accidents or incidents.

I. Introduction

Automation plays a significant role in today's commercial aviation system and future concepts are proposing increasing levels of automation and autonomy. However, "a well-trained and well-qualified pilot has been, is, and will be the critical center point of aircraft safety systems and an integral safety component of the entire commercial aviation system."¹ Pilots serve as the last line of defense in commercial aviation today. They routinely apply their skill, expertise, and knowledge of an ever-changing flight context, to manage aircraft systems during a plethora of complex situations that may arise during a flight. This task requires effective monitoring, decision-making, and action to complete the flight objective while remaining cognizant of safety margin. Further, when and if this margin deteriorates, the pilot is responsible for changing the flight objective or circumstance such that an accident or incident is avoided.

Under this backdrop, the National Aeronautics and Space Administration (NASA) has established the technical challenge, under the Aviation Safety Program, Vehicle Systems Safety Technologies project, to improve crew decision-making and response in complex situations. The specific objective of this challenge is to develop data and technologies which may increase a pilot's (crew's) ability to avoid, detect, and recover from adverse events that could otherwise result in accidents/incidents.

In response to several recent accidents and incidents, NASA has initiated within this technical challenge a cooperative industry-government research program to develop innovative flight deck-based counter-measures that can improve the crew's ability to avoid, detect, mitigate, and recover from unsafe loss-of-aircraft state awareness that can lead to loss of control (LOC). This work specifically targets when a pilot (crew) may experience the loss of attitude awareness (i.e., Spatial Disorientation, SD) or the loss-of-energy state awareness (LESA).

A critical component of this research will be sufficient and appropriate testing and evaluation of crew decision-making. The challenge is to develop *specific and quantifiable* metrics which identify decision-making and the decision-making influences which can be employed during simulation and flight testing. Metrics are critical to

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develop appropriate and effective methods to improve decision-making. Further, metrics may provide a means of real-time identification and active feedback or mitigation on the flight deck.

II. Background

Casual and contributing factors to LOC have been analyzed (e.g., Ref. 2) since it remains one of the largest contributors to fatal commercial aircraft accidents worldwide.

Of particular note, Bramble of the National Transportation Safety Board (NTSB) noted that “the occurrence of several major accidents involving flight crew SD in large commercial airplanes in the last decade marked SD as a phenomenon that deserves the attention of the international aviation safety community.”³ Bateman⁴ further articulated that LOC accidents hold the highest risk for fatalities. Surprisingly, Bateman’s analysis showed that approximately 70% of these accidents are due to SD (the “Spatial Disorientation” and “Reversion to Eastern Attitude Direction Indicator (ADI)” categories cited in Ref. 4) or LESA (“Low Airspeed” cited in Ref. 4).

A. Spatial Disorientation (SD)

SD is an incorrect perception of one’s linear and angular position and motion relative to the plane of the earth’s surface. In the flight environment, SD is an erroneous perception of aircraft attitude, especially in cases where there is limited or no external visibility, and a misperception of attitude information otherwise displayed on the flight instruments.⁵

SD counter-measures have been fairly well-researched especially within the military aviation domain. This research has primarily addressed high performance aircraft (with only a few notable exceptions),⁶ because these vehicles are typically flown single pilot, have demanding pilot workload and mission tasking, and routinely fly at extreme attitudes and with acceleration capabilities that can create significant visual and motion illusions.⁵

The accident statistic data of Bramble³ and Bateman⁴ are surprising in comparison because civil transport category aircraft (14 Code of Federal Regulations, Part 25) adhere to rigid principles for the design of primary cockpit instrumentation, are operated by a crew (two pilots) who are well trained and experienced in instrument flight conditions, and whose maneuvering is very benign. One would expect that the likelihood of SD contributing to an accident should be extremely low.

B. Loss-of-Energy State Awareness

Loss of Energy State Awareness by the crew is typically characterized by a failure to monitor or understand energy state indications (e.g., airspeed, altitude, vertical speed, commanded thrust) and a resultant failure to accurately forecast the ability to maintain adequate airspeed and energy for safe flight conditions. The leading consequence of LESA is aircraft stall.

Significant international research, development, and regulatory work is being performed on aircraft stall and upset, especially as it relates to pilot training of possible LOC/LESA in low speed approach-to-stall and stall conditions (e.g., see Ref. 7 for a summary).

C. The Need for Research and Development?

Although significant work is being or has been done for LOC due to low speed/stall and although there is an abundance of existing data on SD counter-measures, closer scrutiny of the data and the undercurrents and trends that are emerging have prompted a dedicated research and development effort for SD/LESA counter-measures.

For instance, Bateman’s data⁴ pointed out that most of the LOC accidents occur in operations outside North America, Australia, Japan, and Europe. Bateman hypothesized that “the lack of pilot experience and training are significant factors” in this statistical discrepancy. The more important question to be answered is whether these accidents are truly unique to operations outside of North America, Australia, Japan and Europe or are they are just the ‘leading edge’? Will the lack of training and experience that Bateman suspected to be a casual factor in these accidents catch up to the changing demographics and experience levels for the new generation of pilots entering service into North America, Australia, Japan and Europe service (e.g. pilots with/without military or crew resource management training)? Are there design or operational characteristics that exacerbate the decision-making abilities of these foreign crews?

Further, the Next Generation Air Transportation System (NextGen) is going to create new operational paradigms which put the aircraft into tighter spacing and time constraints and may stretch the decision-making abilities for these crews especially due to:

- Greater prevalence of automation.

- More frequent operations in close proximity to weather and terrain (e.g., Required Navigation Performance and Area Navigation (RNP/RNAV)).
- Aircraft operations closer to performance limits (e.g., optimized descent profiles).

D. Flight Deck Counter-Measures

NASA is undertaking a coordinated program of research, development, test, and evaluation of new flight deck-based counter-measures that can improve the crew's ability to avoid, detect, mitigate, and recover from potential SD/LESA accidents and incidents. The goal of the counter-measures is to create:

- a) Awareness, to provide pilots with information regarding the aircraft state or hazard.
- b) Understanding and avoidance of aircraft state and hazards including the projection of the state and hazard conditions should the present course of action continue.
- c) Recovery skills (e.g., training), such that the knowledge, control techniques, and procedures required to accomplish a safe recovery when a lack of awareness or an inability to avoid or mitigate hazards has resulted in the onset of an aircraft upset.

III. SD Counter-Measures

SD research has well-established that the pilot's vision is, by far, the most important sensory system for establishing and maintaining spatial orientation during flight.⁵ In the SD accidents analyzed by Bateman, the loss-of-visual outside horizon references were cited as contributing to the pilot's SD.

A. Visual Dominance

Visual dominance exists when the pilot receives through the eyes all the information used to maintain correct orientation.⁵ Pilots are trained to recognize the importance of visual dominance and vestibular suppression but only through experience and proficiency can vestibular suppression be made easier – not eliminated – but *easier*.⁸

The term ambient vision is often used to describe this visual component of spatial orientation as it refers to the fact that we are not typically consciously aware of the inputs.⁵ Research has established that the pilot's ambient vision is, by far, the most important sensory system for establishing and maintaining spatial orientation during flight. This visual dominance is critical in establishing and maintaining a pilot's spatial orientation during flight.

Approximately 90% of the sensory inputs that a human uses for a sense of orientation are visual and of these, 90% are peripheral vision (where peripheral vision is often defined as the vision off of the optic axis and foveal vision is only in the central two degrees around our direction of gaze.)⁹

Historically, the design of an aircraft's cockpit instrumentation has been tailored to address a crew's need to fly under instrument conditions including: 1) control (i.e., attitude); 2) performance (i.e., energy state); and 3) navigation (i.e., position relative to desired flight path). The potential for SD is considered in the design and in the training of pilot's to use this information, but the display of this information is essentially a foveal, not ambient visual stimuli (see a state-of-the-art design in Figure 1).



Figure 1: Boeing 787 Flight Deck Displays 5 display units – 12-inch x 9-inch each (from Ref. 10)

B. Primary Flight Display Test and Evaluation Metrics

Quantitative design, test, and evaluation standards for cockpit displays to meet these instrument flight requirements, including spatial disorientation prevention (e.g., ‘visual dominance’) are not prevalent. Regulatory requirements and design standards are contained in AC25-11 for instance, but specific quantitative guidance for SD prevention and visual dominance are not on hand. AC25-11 specific guidance suggests that:

An accurate, easy, quick-glance interpretation of attitude should be possible for all unusual attitude situations and other “non-normal” maneuvers sufficient to permit the pilot to recognize the unusual attitude and initiate an appropriate recovery within one second. Information to perform effective manual recovery from unusual attitudes using chevrons, pointers, and/or permanent ground-sky horizon on all attitude indications is recommended.

After a rash of SD accidents, the United States Air Force faced a similar predicament in the certification of flight instrumentation. The approach taken was to establish a working group of subject matter experts to address the deficiencies in the design and development of primary flight instrumentation.¹¹ As part of this work, test and evaluation standards were created. Absolute standards were not practical but the concept that emerged was one of a ‘comparative baseline’ (analogous to Beringer’s subsequent work of equivalent levels of performance and safety¹²) (ref: Weinstein et al). The comparative baseline was a ‘standard’ head-down display instrument suite.¹³

Three instrument flight tasks were developed to test the adequacy of the primary flight instrumentation: 1) an Instrument Landing System (ILS) approach and landing; 2) a precision instrument control task (PICT); and, 3) unusual attitude recovery. A key element of these tasks were test and evaluation standards.

- The ILS standards reflect typical approach and landing performance standards¹⁴
- The PICT standards emerged from pilot proficiency performance standards where the pilot’s ability to control the aircraft using the primary flight information is graded using exceedance or ‘bin scores’ criteria against established Vertical S-D maneuver criteria from aircrew standardization/evaluation programs, such as outlined under Air Force Instruction 11-202.
- The unusual attitude criteria were more challenging to develop. Quantitative criteria were critical to allow accurate and automated processing of the data to ascertain correct or incorrect pilot recognition and recovery control actions. Standards for fighter type aircraft have been developed and are relatively straight-forward.¹⁵ For a transport category aircraft, unusual attitude recovery criteria, shown in Table 1,¹⁶ are not as straight-forward.

Table 1. Initial Conditions And Recovery Input Scores

UAR No.	Initial Condition		Initial Roll Input			Initial Pitch Input			Initial Throttle Input		
	Pitch Att. (deg)	Roll Att. (deg)	Left	None	Right	Fwd	None	Aft	Mil	None	Idle
1	+15	+15	0	1	1	1	0	0	1	0	0
2	+15	-60	0	1	1	1	0	0	1	0	0
3	-10	-30	0	0	1	0	0	1	0	0	1
4	-10	-45	0	0	1	0	0	1	0	0	1
5	-10	+60	1	0	0	0	0	1	0	0	1
6	-20	+30	1	0	0	0	0	1	0	0	1
7	-20	+45	1	0	0	0	0	1	0	0	1
8	-20	-60	0	0	1	0	0	1	0	0	1

Unintentional conditions for transport category aircraft¹⁷ are described by:

- Pitch attitude greater than 25 deg, nose up
- Pitch attitude greater than 10 deg, nose down
- Bank angle greater than 45 deg
- Within the above parameters, but flying at airspeeds inappropriate for the conditions

The attitudes shown in Table 1 skirted the boundaries for unintentional conditions for transport category aircraft and yet remained within accordance with the safe operating limitations of the test aircraft. These criteria also parallel standards and methods used for fighter aircraft testing.¹⁵ In creating these quantitative criteria several considerations were important:

- The criteria of Table 1 show that multiple inputs can be correct. The absence of an action is sometimes correct.
- A masking maneuver was flown, not intending to disorient the pilot, but to mask the attitude for recovery. This creates an element of startle, requiring the pilot to recognize the aircraft attitude and then effect the proper recovery.
- The procedures called for the subject pilot to hold their finger tips on the controls or place their hand near the controls while a masking maneuver was performed. If their hand was on the controls, the subjects might introduce inadvertent inputs or be able to follow the masking maneuver. Once the attitude was reached, a tone was signaled and the subject pilot began the recovery.
- Thresholds were applied to identify the initial inputs. Pitch, roll, and throttle inputs that first exceeded values of 5 lbs in pitch stick force, 3 lbs in roll stick force and 0.4 inches in throttle movement signified a pilot's intentional input to recovery. These thresholds were critical to eliminate inadvertently counting non-significant, unintentional inputs especially as the pilot grabs the stick after the tone sounded.
- Similar criteria have been used by others, as well as augmented by additional criteria such as whether the crew disconnected the auto-throttle and/or auto-pilot, maximum and minimum speed, stick shaker occurrence, or stall.¹⁷

The test methodology, such as having the pilot use fingertips on the controls, and threshold criteria can significantly influence the measured recovery times. Data from Gawron¹⁶ in Figure 2 shows initial inputs for recovery were not always below 1.0 sec as per AC25-11 (even though the data suggest that excellent attitude awareness was provided by the test primary flight instrumentation). Unusual attitude recovery for an F-16 using a HUD format showed recoveries greater than 1.0 seconds as well, averaging about 1.4 to 1.5 seconds time to first input (i.e., reaction time) with 96 to 99% response accuracies.¹³

Time to recover and altitude lost have been used as UAR criteria. These criteria are logical but they are also problematic, especially in simulation.

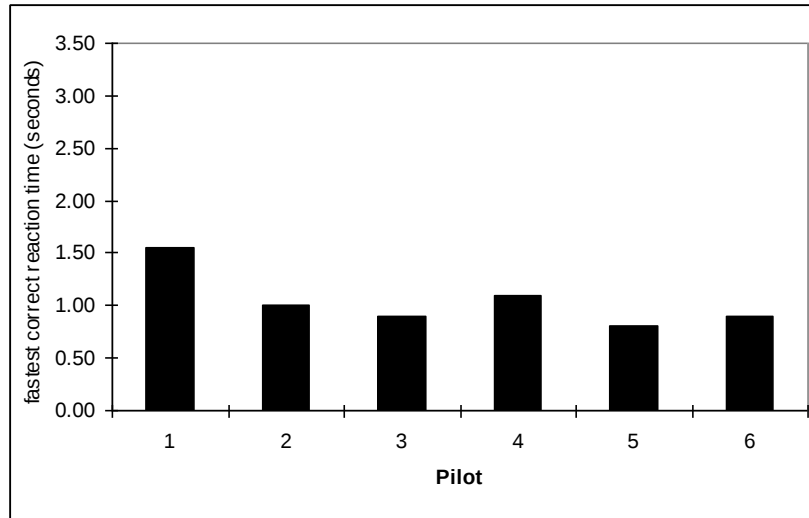


Figure 2. Fastest Correct Reaction Time per Pilot (From Ref. 16)

C. Flight Vs. Simulation Metrics

Simulation is a powerful tool in research and development but its limitations must be recognized.¹⁸ One of the difficulties in administering accurate, representative test and evaluation metrics for aircraft upset recoveries is the lack of full motion cuing in a ground-based simulator, even one as capable as a Level D simulator. These simulators lack the accelerations that might be encountered in entry or recovery from these extreme upset conditions. Using altitude loss or time-to-recover as criteria will exacerbate this deficiency.

The work by Ward and Moreau¹⁹ highlighted how, without ‘calibration’ to the flight environment, MD-11/A-300 pilots often exceeded g-force targets for the upset recoveries, some pulling as much as 8 g’s in full-flight simulators. Lacking the g-cues associated with actual flight, the pilots tended to over control in an effort to expedite recoveries in the full-flight simulator (FFS). This led to gross control inputs and over-g conditions. (In contrast, during program development flight tests in the MD-10, MD-11, and B-747 airplanes, the same pilots performing pitch-up maneuvers to a 30° nose up attitude displayed the opposite effect; very slow and deliberate control inputs with very timid control input magnitudes, often leading to a rapid loss of energy which would have put the recovery in jeopardy were it allowed to continue.) Based on these observations, a digital g-meter readout was added to the HUD upset recovery symbology set to help guide the pilots into pulling or pushing to proper g-targets in both flight and ground-based simulation. In the development of a USAF HUD for primary flight, an audible g-tone was added in simulation (and in flight for experimental consistency) to signal to the pilots when a desirable g-level was being pulled.¹⁵

Unusual attitude and other testing primarily examines the ability of the pilot to use foveal visual display and vestibular suppression to effect a return to safe flight control conditions, since testing is usually conducted in simulated or actual instrument meteorological conditions (IMC). Testing of SD illusions using hexapod motion base platforms - typical of Level D FFS - shows that the implementation and effective pilot training of vestibular illusions is not feasible but the FFS can provide training for potential spatial disorientation caused by the visual illusions.²⁰

One promising flight maneuver to test the potential for SD – but only possible during flight testing – is the Post-Roll Gillingham Illusion.²¹ The test protocol, as follows, could provide an effective test of sub-threshold roll and visual dominance effects:

1. Subject pilot rolls aircraft into 45 deg bank angle; coordinated flight using the primary flight display under IMC;
2. Subject pilot ceases inputs; test displays are blanked;
3. Auto-pilot/safety pilot performs roll reversal to opposite 45 deg bank angle using a pre-set roll rate;
4. Upon reaching 45 deg opposite bank, a 1 second tone is triggered signaling pilot to regain aircraft control and maintain a stable bank angle;
5. Subject pilot controls aircraft for 15 sec (or until safety pilot takes control);

The data²¹ (example in Figure 3) shows clear evidence of potential SD where the percentage of inputs by the pilots trended toward increased bank (wrong direction) as the roll rate (i.e., post-roll illusion) decreased toward zero. More data are clearly needed to identify the trend toward the sub-threshold roll condition from 10 to zero deg/sec.

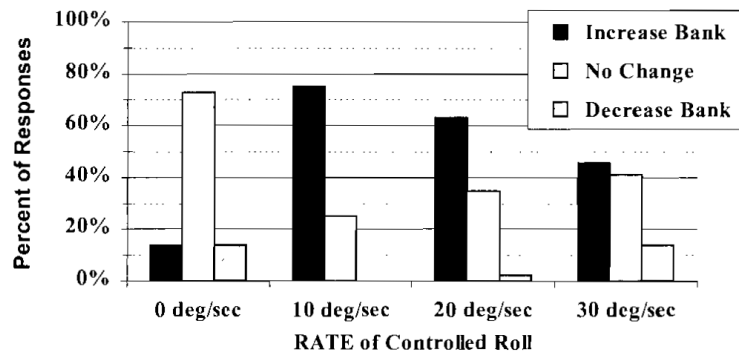


Figure 3. Percentage Of Correct Roll Responses to Post-Roll Gillingham Illusion (From Ref. 21)

D. Visual Dominance – Synthetic Vision?

Synthetic Vision (SV) is a computer-generated image of the external scene topography that is generated from aircraft attitude, high-precision navigation, and data of the terrain, obstacles, cultural features, and other required flight information. NASA established a SV program in 1999 expressly to develop the technology for an electronic means of displaying in the cockpit intuitive visual-like flight references to provide significant improvements in terrain awareness and reductions in the potential for Controlled-Flight-Into-Terrain incidents/accidents. As Bateman⁴ noted, “if the pilot can see the horizon clearly outside the aircraft, the probability of loss of control is probably very low. The Synthetic Vision System (SVS) display does just that by bringing a ‘daytime clear visibility’ synthetic outside view into the cockpit ‘heads down’ into an overlay of primary flight instruments similar to those found on a Head-Up Display (HUD).”

The use of an SV display, as opposed to an abstract analog of blue-over-brown, certainly seems intuitive for SD prevention. As a minimum, the SV display seems ideally fit to once-and-for-all resolve the outside-in, inside-out attitude indicator debate.²² Changing the abstract nature of the display to be an intuitive earth-reference should eliminate any training effect or bias that an Eastern-trained might have and directly address the “Reversion to Eastern Attitude Direction Indicator” category of accidents as cited in Bateman.⁴

Beringer et al¹² evaluated the concept to determine if primary flight displays (PFDs) depicting terrain could be used with a level of safety equivalent to electronic attitude-direction indicators (EADIs) without terrain. Using 5 groups of 8 pilots each in a fixed-based ground simulator, unknown (unusual) attitude recoveries were performed using one of three PFD concepts (EADI – baseline, blue-over-brown; full-color terrain SV; and, uniformly-brown terrain SV), with and without recovery guidance symbology. Performance standards (initial response time, total recovery time, and both initial and secondary control reversals) showed no statistically/operationally-significant differences across the groups. The recovery guidance received a positive response from the pilots but the performance data was unaffected. The most significant factor seemed to be the presence of a prominent zero-pitch line (i.e., horizon line) that allowed the pilots to discern their attitude and to perform recoveries from unknown attitudes regardless of the terrain format.

The prominence of symbology and other salient cues has been shown to be critical to effective recovery for cockpit instrumentation. In the evaluation of a HUD standard for the USAF,¹¹ the asymmetric nature of the HUD pitch ladder was well-received but the articulated pitch ladder lines nose-up were a significantly better awareness cue than the tapered nose-down pitch lines. The zenith and nadir symbols were extremely salient and provided instantly recognizable and actionable symbology for recovery.

Ward and Moreau¹⁹ evaluated specific symbology tailoring on the HUD for recoveries from extreme attitudes. The nominal symbology was decluttered and tailored for unusual attitude recovery, including guidance cue removal, changing to airspeed and altitude digital readouts with trend indicators for energy awareness, and adding AOA for awareness of wing loading. Interestingly, the EFVS image was also removed since “during development, it was noted that there were times when differentiating between cloud details and ground surface details was difficult for the inexperienced eye.”

E. Visual Dominance – Peripheral Displays?

These data suggest promise for the application of SV technology for establishing a visual analog – thus, creating ambient visual mechanisms for spatial orientation – but significantly more research is needed.

For instance, in Beringer's work,¹² the SD display subtended approximately 16.4 deg H by 12.3 deg V, while portraying 30 deg laterally of the outside world (i.e., minification factor of approximately 2.0). Previc²³ noted that "studies have shown that little vection (visually-induced motion perception) is produced by visual stimuli within the central 50 degrees." What is the field-of-view (FOV) required for visual dominance?

The fact that visual dominance occurs readily in the real-world under normal daylight conditions provides guidance to synthetically creating it. Advisory material for the design of aircraft windows, specifically Advisory Circular (AC) 25.773, is examined.

This advisory circular (AC) sets forth a method for demonstrating compliance with the airworthiness standards for transport category airplanes pertaining to pilot compartment view. (As with all ACs, the guidance material is not mandatory and does not constitute the only means of compliance to regulations.) This AC outlines the natural vision that the pilot of a commercial transport aircraft would have during visual meteorological conditions. In Figure 4, the visual area of the windows from the view of the Captain is shown. The data shows the out-the-window visual area as a function of the azimuth (left/right) from the design eye reference point, DERP. (Zero degrees azimuth is looking forward along the aircraft fuselage.) This data shows that the display area is greatest in the pilot's left periphery (i.e., from -50 to -100 deg in azimuth).

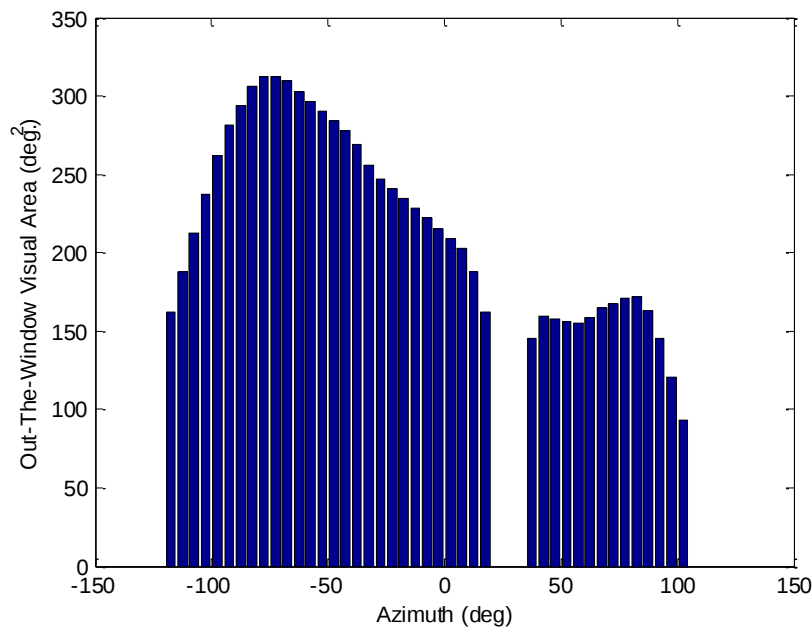


Figure 4: Out-the-Window Visual Information per AC25.773

The out-the-window visual area metric provides a baseline metric, albeit a very lofty goal.

The research to date²³ also suggests the following general requirements for synthetically-generated visual dominance:

- 1) Wide FOV subtending at least 60 deg and preferably >100 deg in extent, with 'correct' spherical projection of the horizon;
- 2) Optical scenes should be optically projected at a distance that exceeds the effective range of most binocular mechanisms (>5 m or preferable, larger);
- 3) Temporal resolution to match the realism and believability of the imagery compared to an out-the-window scene (<100 msec latency); without aliasing, flicker or other optical defects;
- 4) Spatial resolution is not critical in the periphery but must promote image realism (>0.5 min of arc spatial resolution);
- 5) Sufficient content to both stimulate the ambient visual system and create the level of detail expected of a real-world daylight scene. The synthetic scene must believably represent the movement of Earth-fixed space.

Attempts to create synthetically-derived visual dominance have been more or less successful.

One study showed that with a very wide FOV and nearly collimated (58 deg V x 114 deg H FOV) daylight scene, the somatogravic illusion could be broken for pilot subjects.²⁴ Pilot subjects were visually coupled to the

scene in both simulated night and full-day scenes, breaking the somatogravic illusion. However, the data used both pilot and non-pilot subjects. The somatogravic illusion was not always broken for non-pilots. The study concluded that pilots perceive pitch rotation in a different way than non-pilots, implying differences in accommodating an interaction between the semi-circular canal and otolith system information. These data indicate that pilots must be used in any study of visual/motion perception in flight or simulated flight conditions. This work has serious implications for experience and training. Does the flying experience and training differences between military and commercially-trained pilots matter? Is SD training required for commercial transport pilots? What are the training recurrency requirements?

F. Background Attitude Indicator (BAI)

Stimulation of the peripheral, ambient vision is a precursor for visual dominance. A Peripheral Vision Display device was designed to take advantage of our subconscious processing of peripheral vision information for spatial orientation and balance.⁹ The first-principles of the concept were successfully demonstrated to create visual dominance/vection especially in roll but the concept suffered somewhat by the limitations of the technology at the time. To date, large inside-out designs that span the entire cockpit (like the Peripheral Vision Device) have not proven to be completely successful in eliminating attitude interpretation problems, including those associated with roll-reversal errors.²³

An alternate approach to create an ambient vision means of visual dominance –such as the Peripheral Vision Display – was the background attitude indicator (BAI).²⁵ During fighter aircraft-type unusual attitude recoveries, no statistically and operationally significant results were found in comparison between baseline (no-BAI EADI) and BAI conditions. The pilot subjective preference data highlighted important design considerations for the BAI such as horizon line depiction, texturing and coloration of the background information, and visual extent of the BAI. The subjective data showed that color shading and texture of the BAI provided the best visual information. These findings correspond nicely to Previc's requirements for visual dominance in that there should be "sufficient content to both stimulate the ambient visual system and create the level of detail expected of a real-world daylight scene."

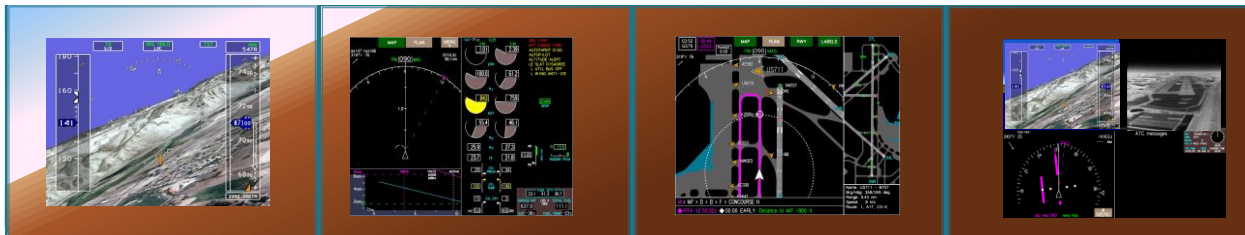
In the two studies from Liggett and Reising,²⁵ the visual extent of the BAI was limited. In the first study, a single 8"x8" display was simulated with BAI drawn around a 6"x6.5" EADI. In a second study, the BAI was drawn across three simulated electronic displays, tiled side-by-side.

The BAI concept is illustrated for a commercial transport aircraft in Figure 5. In Figure 5a, the BAI concept is drawn using all four display devices, like that used in Figure 1. The reference point for the SV background is the Captain's EADI.

In their second study, Liggett and Reising²⁵ varied the BAI reference point – i.e., whether one reference in the center display was used and the BAI extended across the three display units or whether a BAI was referenced to each display unit individually. For this single seat cockpit application, there was a preference for using the BAI across multiple displays to provide a continuous reference, like that of Figure 5a.

However, should the reference be the left seat (Captain's) ADI (Figure 5a) where the BAI matches the Captain's ADI but is offset for the Co-pilot's or instead, the center of the panel (Figure 5b) where the BAI is not offset for both pilot's ADI? Or should it be split across the four panels (Figure 5c) so each ADI is properly referenced but two BAIs are seen? While good information, the reference point research question remains unanswered for side-by-side, two seat installations.

a) Referenced to Captain's ADI



b) Referenced to Center of Panel



c) Referenced to Each ADI



Figure 5: Background ADI Options for Two-Seat, Side-by-Side Cockpit

In the two studies of the BAI,²⁵ the visual extent of the ambient information was relatively miniscule (Figure 6, ‘BAI - Single EADI’ and ‘BAI - Tiled EADI’) compared to the out-the-window view (Figure 4 – note scale change). The original work was trying to address the single-seat fighter type cockpit with little available instrument panel space so this result is understandable – a significant vection/visual dominance effect should not be expected.

If a one-inch area around the periphery of displays like Figure 1 (or Figure 5) is used, more ambient vision may be stimulated (labeled ‘1” BAI New Display’ in Figure 6). But still, the visual area pales in comparison to the out-the-window. For reference, if the entire instrument panel like Figure 1 were used as a BAI the ambient vision stimulation (‘Use Entire Display Surface’ in Figure 6) is finally approaching the magnitude created by windows.

Even if the visual extent is sufficient, questions remain as to whether this BAI concept display would be far enough from the DERP so that the imagery does not invoke binocular vision mechanisms (see Previc’s Criteria 2 above). The distance is certainly not 5 m, more like 1 m.

Further, questions remain as to the sufficiency of the synthetic scene detail (Previc’s Criteria 5 above) to create visual dominance. Fortunately, computer-generated imagery computing has grown tremendously for flight simulation application and aircraft instrumentation, enabling concepts such as Synthetic Vision.¹⁴ Metrics are emerging to quantify a virtual scene²⁶ and its ability to promote realism or presence. The metric, termed ‘spatial velocity’ looks promising as a way to quantify the characteristics of scene content and optical flow as a test for visual dominance.

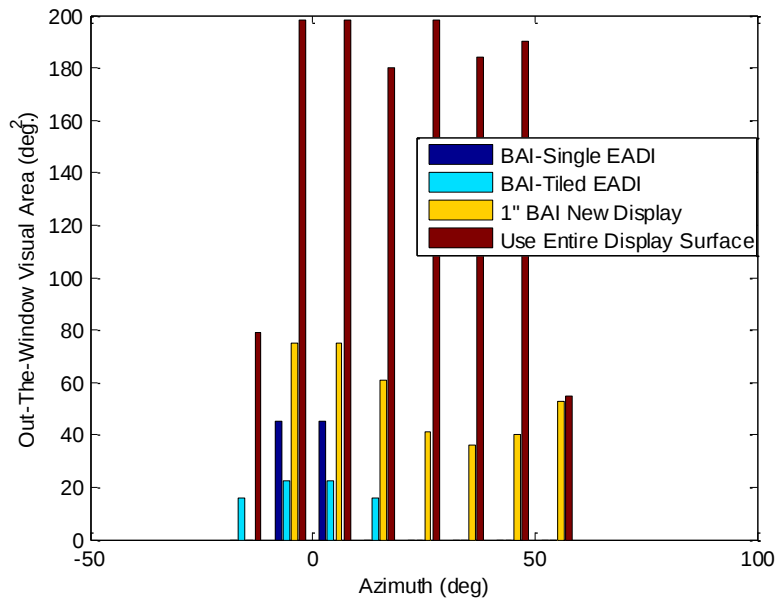


Figure 6. Visual Area Subtended by BAI Concepts

IV. Channelized Attention and Crew Workload

The preponderance of SD accidents and incidents in two-crewed airplanes suggest that there is a break-down in the pilot monitoring function: the pilot-flying experiences an SD-inducing event but the pilot-monitoring was unable or ineffective in preventing the SD event from causing an accident or incident.

Effective monitoring and cross-checking can literally be the last line of defense, enabling a break in the chain of events leading to an accident or incident. One way to create effective monitoring and cross-checking is to develop automated methods of monitoring – essentially adding another layer of cautions and warnings driven around the error catching and cross-checking done by the human today. While this step may be possible, it is a formidable task considering the vast array of conditions, operations, and tasking that are currently covered by the pilot-monitor. Further, the flight deck is already littered with disparate alerts. Adding more alerts may do more harm than good.²⁷

Sumwalt et al²⁸ identified four underlying causes of poor monitoring by the human: a) industry has not made pilot monitoring a primary task; b) the current system does not reward proper monitoring; c) continuous and effective monitoring is not natural; and d) effective monitoring leads to boredom and complacency. “While it may be true that humans are not naturally good monitors, performance can be significantly improved.” Although boredom and complacency are clearly problems with proper monitoring, the other extreme, also possibly as problematic, is channelized attention and excessive pilot workload.

As described in Wickens,²⁹ channelized attention or attentional tunneling is the allocation of attention to a particular channel of information or task goal for a duration that is longer than optimal given the cost of neglecting events on other channels or failing to perform other tasks. The accident or incident concern is when one or both pilots (pilot-flying or pilot-monitoring) are attending to a task at the exclusion or omission of monitoring the pilot-flying or properly attending to the operation of the aircraft and/or automation.

A. Channelized Attention Monitoring

Instead of adding new layers of alerting, a different approach to ensure proper attentional direction might be to create technology that “monitors the monitor” as well as the pilot-flying. The technology identifies when effective monitoring isn’t occurring.

Active and focused monitoring are vigilant behaviors that differ in the distribution of attention within an effective range.³⁰ Active monitoring refers to a wide scope of awareness, whereas focused monitoring describes a narrower, yet effective, scope of awareness prompted by necessary flight procedures or at times discovery of an anomaly. Attentional focusing becomes hazardous when it results in an individual being oblivious to all but a few elements in the present environment and shifting to a wider awareness is not considered. The state of absorption can

also be described as hypnotized, over-focused, excessive concentration, and forgetting the big picture. The cognitive experience has been termed attentional "tunneling" and "channelization,"³¹ and is similar in result to the attentional narrowing reported in certain high stress situations.³² Whereas the state of absorbed attention can be desirable and beneficial for short term problem solving, it can be hazardous for those who monitor systems for long periods of time such as aircraft flight crew.

B. Psychophysiological Monitoring

The questions become: Can technology be used to improve pilot monitoring or identify when a pilot fixates or channelizes their attention to the exclusion of other tasks and information channels?

Methods have been employed in laboratory and operational settings to track attention using non-invasive psychophysiological measures, including electroencephalography (EEG), electrocardiography (ECG)^{33,34} and functional near-infrared spectroscopy (fNIRS).^{35,36}

The state-of-the-art use of EEG to determine various levels of operator functional state rely predominantly on analysis of frequency domain measures derived from raw EEG. The basis for this use of EEG is the associations of separable EEG frequency bandwidths, to the states of awareness or mental activity identified in the scientific literature. These frequency bands and their distribution across the cortex of the brain are typically used individually or through some formulaic comparison to define real-time or near real-time operator functional state. Current approaches to assess specific mental faculties such as task engagement or attention have been based on relative prevalence of high frequency EEG activity which tends to occur during high workload task performance.³⁷⁻³⁹

Cardiovascular activity has been demonstrated to indicate real-time workload experienced by operators of complex systems.^{40,41} Specifically, ECG-derived indices reveal human autonomic nervous system (ANS) activity or arousal. The ANS employs feed-forward (from the central nervous system, or CNS, to the periphery) and feedback systems (from periphery to the CNS) to regulate internal bodily states. The parasympathetic nervous system (PNS) is the branch of the ANS controlling homeostatic or resting functions. The sympathetic nervous system (SNS) is the arousing (i.e., "fight or flight") control system for the body. Assessment of heart activity provides a window into a predominantly SNS stress response to excess workload during acute incidents which can occur on the flight deck. Additionally, mental processes such as attention are reflected in the fluctuation of the activity of the ANS. Appropriate monitoring of a multi-task environment such as the flight deck would involve a PNS response to stress including attention that is flexible.

A time series of the intervals between each consecutive heart beat can be derived from the non-invasive ECG of an operator while they are performing operational tasks. The "high frequency" (0.15 and 0.5 Hz) of the spectral analysis of ECG time series provides a measure referred to as respiratory sinus arrhythmia (RSA). RSA is a noninvasive, objective cardiovascular index which allows for assessment of the parasympathetic activity of the ANS.^{42,43} Research has demonstrated that RSA serves as an effective metric of workload specifically in high workload conditions.⁴⁴ Furthermore, research supports the theory that in the face of environmental challenges, flexible parasympathetic nervous system functioning is an important component of adaptive stress regulation.⁴⁵

fNIRS is an emerging portable brain imaging technology. In general, it provides rich potential to supplement behavioral data with objective neural hemodynamic measures in real-world contexts toward the identification of operator state. Real-time processing allows monitoring during the actual performance of real world tasks. When combined with real-time state classification processing, this allows for long-duration monitoring and potential use in brain-computer interfaces (BCI) applications.^{46,47} fNIRS has been applied to a train driving simulation task comparing manual and automated modes⁴⁸ and to the development of a robot which adapts to the multitasking state of a human operator.⁴⁹ Although promising, the need for improvement remains regarding the reliability of fNIRS measurements in operational contexts, the specificity of state detection, and the standardization of signal processing techniques in the research field. The great strength of fNIRS is that it can be used to detect cognitive states now only detectable with high fidelity function Magnetic Resonance Imaging in brain activation regions in the cortex.⁵⁰

C. Eye Tracking

Eye tracking provides a direct measure of a pilot's eye gaze and possibly, attention across the flight deck. The basic metrics that define eye movement, fixations, and saccades are more general quantifying measures. Environment-specific measures such as area of interest (AOI), dwell time, and 'link analysis' (e.g., tying eye gaze to aircraft state data) provide context-specific elements that can be utilized to quantifiably assess pilot attention and infer pilot situation awareness. Eye tracking can be done remotely for non-invasive data collection - a capability that makes eye tracking very appealing to human-in-the-loop research activity.

Utilization of gaze fixation and saccadic movement metrics have been prevalent in research for several years in an effort to define a global behavioral relationship between eye tracking metrics and a subject's attention and state.

For example, fixation duration has been observed to correlate inversely with eye scan efficiency, and correspondingly efficiency has been proven to correlate inversely with workload.⁵¹ Maximum and minimum fixation duration and fixation frequency are common measures that have been found to be significantly impacted by variable cognitive tasking. Longer fixations have been found to be indicative of increases in cognitive processing loads.⁵² Increased fixation frequency has shown to represent a more effortful search, suggesting poor performance accuracy and longer search times in memory tasks.⁵³

Other measures such as scan path indexing and gaze entropy have also been used to characterize differences in eye movement behavior and associate them with specific eye movement behavior to define a state of being.^{54,55} Such findings lead to general definitions to characterize a pilot's state from global metrics, however, these measures leave out the contextual information that is derived from coupling such metrics with AOI information. This context-specific information is necessary to determine where and why a pilot is devoting attentional resources and to what degree.

Wickens⁵⁶ suggests that there are three possible factors engaged in concurrent task management and their performance outcomes: confusion, cooperation, and competition. These factors may be associated with visual resource allocation and a pilot's attention. Confusion is the condition where tasks that are similar interfere with the overall performance, while more distinct tasks have a less frequent degradation to performance. Cooperation is described as task processes that are similar and yield combined results. Competition of resources, particularly observable when driving the allocation of one resource versus another, results in a decreasing supply of resources for other tasks being managed. The argument is that cooperation between tasks improves when they use separate, instead of shared resources.

Expanding on this theory, a contentious argument is that there is not a distinct number of resources available for an individual. Some believe there are multiple pools of resources as opposed to a single generic pool.⁵⁷ Regardless of the pools of resources being utilized - be it one or several - it is not a single source of information that is going to ultimately characterize an individual or a crew of individuals, but a composition of several sources of information. This makes any logic-based inferential information useful to predicting performance when such data is available, such as known task difficulty from aircraft state information and indicators of pilot attention and operator state derived from eye tracking.

D. Crew State Monitoring

Each of these psychophysiological measures and methods have strengths and limitations but the combined use of these measures has been suggested to provide converging indicators of a more complete assessment of operator state.⁵⁸ Under NASA's SD/LESA counter-measures program, crew state monitoring research is following this work by integrating these technologies for real-time evaluation of the attentional state of flight crew and to identify flight crew work overload and channelized attention. The ultimate goal is to create methods and metrics which can operationally be employed to mitigate adverse crew/pilot states in their roles as the pilot monitoring or the pilot-flying.

V. Concluding Remarks

NASA has established a technical challenge, under the Aviation Safety Program, Vehicle Systems Safety Technologies project, to improve crew decision-making and response in complex situations. The specific objective of this challenge is to develop data and technologies which may increase a pilot's (crew's) ability to avoid, detect, and recover from adverse events that could otherwise result in accidents/incidents. Within this technical challenge, a cooperative industry-government research program has been established to develop innovative flight deck-based counter-measures that can improve the crew's ability to avoid, detect, mitigate, and recover from unsafe loss-of-aircraft state awareness – specifically, the loss of attitude awareness (i.e., Spatial Disorientation, SD) or the loss-of-energy state awareness (LESA). A critical component of this research is to develop specific and quantifiable metrics which identify decision-making and the decision-making influences during simulation and flight testing. One of the principal counter-measures to SD may be the use of new visual displays to create and establish visual dominance. The review of previous research and test metrics in visual dominance highlight significant gaps that need to be filled. Certification criteria for visual displays is non-existent for visual dominance, but some data are available for unusual or unintentional aircraft conditions. The development of Crew State Monitoring technologies – eye tracking and other psychophysiological – show promise as emerging new metrics for identifying channelized attention and excessive pilot workload which have been shown to contribute to SD/LESA accidents or incidents. The research to date indicates that combinations or fusion of the different technologies and methods will be necessary. In addition, these data must be merged with context-specific elements, such as area of interest (AOI) or 'link analysis' (e.g.,

tying eye gaze to aircraft state data) metrics to identify where and why a pilot is devoting attentional or workload resources and to what degree.

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